RAND

New Capabilities for Strategic Mobility Analysis

Executive Summary

John F. Schank, James P. Stucker,
Michael G. Mattock, Jeff Rothenberg

National Defense
Research Institute

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PREFACE

This report documents part of a RAND project entitled "Achieving Maximum Effectiveness from Available Joint/Combined Logistics Resources." The research was sponsored by the Logistics Directorate of the Joint Staff (JS/J4) and was conducted under the Acquisition and Support Policy Program of RAND's National Defense Research Institute, a federally funded research and development center sponsored by the Office of the Secretary of Defense, the Joint Staff, and the defense agencies.

The first two tasks of the project surveyed the needs and opportunities for responsive logistics/operations command, control, and communication, and conceived and evaluated enhancements for conventional ammunition (Moore et al., 1989; Schank, Stucker et al., 1991). The objectives of the third task under the project were to understand and improve the capabilities of the major computerized models and databases used by the directorate for analyzing strategic mobility questions, to survey the various uses of strategic mobility models, to evaluate major existing models, and to determine whether another computer model would serve the directorate's needs better than its current models.

The third task found numerous shortcomings with mobility models and suggested that a new knowledge-based simulation environment of the kind being developed at RAND under Advanced Research Projects Agency sponsorship could eventually provide improved credibility, verifiability, and shorter turnaround times. The third task also found that the models currently used by the Joint Staff were inappropriate for its most important type of mobility analyses, those

attempting to identify preferred or least-cost mixes of force availability, transport assets, and prepositioning. It recommended that those broader-based trade-off analyses be addressed using new formulations of traditional mathematical-programming procedures and off-the-shelf software (Schank, Mattock et al., 1991).

This report summarizes the results of the fourth task, which developed knowledge-based prototypes and demonstrated mathematical-programming formulations designed specifically for the Joint Staff mobility analyses. Two companion reports detail the modeling and analyses activities and achievements:

Rothenberg, Jeff, James P. Stucker, Michael G. Mattock, and John F. Schank, *Knowledge-Based Modeling for Strategic Mobility Analysis*, unpublished RAND research.

Mattock, Michael G., John F. Schank, Jeff Rothenberg, and James P. Stucker, *New Capabilities for Strategic Mobility Analysis Using Mathematical Programming*, unpublished RAND research.

This and the two companion reports should interest mobility analysts and planners throughout the defense community, especially those at the Joint Staff, the Office of the Director for Program Analysis and Evaluation, and the United States Transportation Command.

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INTRODUCTION

Previous research for the Logistics Directorate (J4) of the Joint Staff (JS) found that although the JS/J4 uses mobility models in several distinctly different types of analyses, it usually uses only a single, specialized type of model, a type that is inappropriate for many of the JS's more important analyses (Schank, Mattock et al., 1991).

TYPES OF TRANSPORT STUDIES

In general, the typical military mobility analysis includes information about cargoes (the location of what needs to be moved, when it will be available to move, and when it has to be delivered), about the transport network (distances, throughput capacities, roadbed conditions, right-of-way constraints, etc.), and about transport assets (the number and type of available vehicles, structures, and equipment, and the schedules and costs under which additional or newer types can be procured). Depending on the problem or operation under consideration, these components are grouped and analyzed three different ways.

Studies That Plan Operations

First, studies concerned with planning and executing military transport *operations* (such as in crisis-action or deliberate-planning situations) concentrate on using current or programmed transport capabilities most effectively—on estimating the maximum capability of an existing system to deliver specific sets of cargoes. In transportation terms, the focus falls on routing and scheduling. A *desired* deliv-

ery profile may serve as a guide, but the direct output of the analysis is an estimate of the *feasible* delivery profile. Detailed analyses of these types of activities are conducted by the U.S. Transportation Command (USTRANSCOM) and its operational components (these are called transportation component commands, or TCCs, and are the Air Mobility Command [AMC], the Military Sealift Command [MSC], and the Military Traffic Management Command [MTMC]), using specialized simulation and optimization models. The JS/J4 formerly coordinated and checked those analyses, especially before the establishment of USTRANSCOM in 1986, using detailed but dated simulation models. J4 involvement in those analyses has been diminishing since the establishment of USTRANSCOM.

Studies That Examine Structure

A second major category of military transport studies addresses the structure and makeup of the current and future transportation system, rather than assuming it is predetermined and immutable. These studies analyze the future of military transport and attempt to optimize, or in some way rationalize, its *structure* as well as *operations*. Typically, a TCC that is attempting to evaluate or to integrate new capabilities conducts these studies. For example, AMC evaluates the C-17 cargo aircraft in conventional roles and also analyzes how current operations and systems can best be adapted to complement the C-17's unique capabilities. MSC performs similar studies for ships, shipping, and prepositioned military equipment, and MTMC does the same for port and terminal operations and for transport within the continental United States. Over the past several years, each of the TCCs has been actively acquiring new modeling capabilities. More recently, USTRANSCOM has been designing, acquiring, and coordinating a suite of higher-level models encapsulating major elements of the TCC's detailed models and approximating their major outputs in a context that allows comparisons, coordination, and evaluations. In spite of that activity, however, the JS still has reviewed some of the TCCs', and even USTRANSCOM's, studies, using its own simulation programs for the line-haul studies and several equally dated network-analysis programs for port-operations studies and for analyses of in-theater transport.

Studies That Investigate Broader Trade-Offs

A third type of transportation study investigates *trade-offs* not only among transport modes but also among transport, readiness, and employment. That is, these studies, while still focusing on transport, consider the cargo availability dates, the needed-in-theater dates, and the list of items to be prepositioned, not as "requirements" but as items to be costed or valued and then integrated into a wider, systemwide optimization. These studies, historically undertaken by the Office of the Secretary of Defense (Program Analysis & Evaluation) (OSD[PA&E]) and the JS—organizations with a wider purview than just transportation—relied on optimization models in the 1960s and 1970s. Unfortunately that approach was virtually abandoned, and OSD and the JS acquired and embraced detailed simulations like the Model for Intertheater Deployment by Air and Sea (MIDAS) in the 1980s as management emphasis shifted from rational expansion and updating of transport to efficiently using existing transport. Several recent studies attempted to recapture the broader framework but failed because the current models are inappropriate and because staff had lost the broader perspective.

FOCUS OF JOINT STAFF MOBILITY STUDIES

The JS participates in all aspects of strategic mobility analysis. However, its primary strategic mobility role, demanding the majority of its analytic time and effort, centers on the third type of study discussed above, one that balances troops, transport, and cost issues. For this type of study, JS/J4 analysts seek to identify the "best" mix of airlift, sealift, and prepositioning required for various scenarios.

The JS/J4 has performed a number of major mobility studies over the last decade, including the Revised Intertheater Mobility Study (RIMS), the NATO Sealift Sizing Study, and the recent congressionally mandated Mobility Requirements Study (MRS). For these studies and others performed by JS/J4, the MIDAS model and, to a lesser extent, the Rapid Intertheater Deployment Simulator (RAPIDSIM) model have been the primary analysis tools.[1] Those models capably

[1]MIDAS and RAPIDSIM are discussed in Schank, Mattock et al., 1991. For additional detail see Keyfauver, 1987, and Joint Data System Support Center, 1985.

simulate transport operations, the purpose for which they were designed, but they are not very helpful for analyzing transportation trade-offs.

The RIMS investigated transportation for a revised NATO scenario and found that the set of assets required to move the stipulated force to Europe was so large that available budgets could not procure and operate the fleet. But MIDAS lacked the analytic agility to allow analysts to explore alternative cases easily. Over 400 MIDAS runs were conducted between October 1986 and April 1989 in the study, and the analysts still could not consider the marginal benefits, utility, or cost-effectiveness of alternative sets of airlift, sealift, and prepositioned equipment and supplies.

The recent MRS was even more difficult. In RIMS, at least the scenarios and the movement requirements were generally accepted by all participants. The main problem was the analysis tools. In MRS, however, even the scenarios were disputed. In RIMS (and during the cold-war years) one clearly dominant scenario determined the maximum transport requirements; in MRS no one knew whether any of the scenarios selected were reasonable *or* dominant. The traditional simulation models available to the JS were again unsuitable for the analysis needed in the study.

We expect the trends toward increasing uncertainty and increasing cost-consciousness to continue. With growing frequency, JS/J4 analysts are examining low- and medium-intensity conflicts in diverse regions of the world. These "new" scenarios place different stresses on different portions of the mobility system. Some are airlift intensive; others rely more on sealift; some are within the capabilities of programmed future mobility assets; others require new mixes of troops, transport, and prepositioning.

NEW CAPABILITIES RECOMMENDED

Our 1991 survey documented the shortcomings of the transportation models currently available for JS/J4 use: the MIDAS and RAPIDSIM models, which were designed for operations analyses, are overly detailed for JS/J4 use; they ignore major uncertainties; and they do not facilitate the broader viewpoint required by the JS.

We concluded that the models being used by the JS/J4, those being used by USTRANSCOM and the TCCs, and the models then under development shared a number of significant shortcomings when considered for JS use:

- Most work in one direction only, a direction that is fine for conducting capability assessments but that makes it nearly impossible to determine resource requirements.
- Their credibility is limited to the organizations using them, making it very difficult for several organizations using different models to agree on analysis procedures or outputs.
- They do not recognize uncertainty, presuming to give detailed answers to specific problems.
- Their objective functions are too narrow and rigid for the major JS/J4 analyses.

We recommended that the JS/J4 obtain different models and adopt more general analyses frameworks to overcome those deficiencies. We suggested that both knowledge-based and mathematical-programming procedures could be formulated to directly estimate transportation resource requirements. We proposed developing knowledge-based simulation procedures to increase the capability, credibility, and flexibility of JS/J4 studies of transport operations. And we proposed broader mathematical-programming formulations, allowing the JS/J4 to analyze trade-offs between transport, readiness, employment times, and prepositioning.

PURPOSE OF THIS DOCUMENT

This document summarizes the prototypical models and procedures we developed to provide those capabilities. It describes knowledge-based developments we believe can add enhanced analytic capabilities and understanding to transportation operations and planning, and it describes and demonstrates the mathematical-programming formulations we recommend for analyzing broader force-oriented mobility questions.

Chapter Two

IMPROVED MODELING CAPABILITIES USING KNOWLEDGE-BASED METHODS

Our knowledge-based (KB) research developed from work initiated with funding from the Advanced Research Projects Agency (ARPA) in the early 1980s. By 1991, the development work had become part of an ARPA initiative applying artificial intelligence techniques to transportation planning, and in 1992 we began investigating the application of the methods under JS funding. Several KB techniques promise to be of great value to JS/J4. Within several years, the models should be more transparent and verifiable, should perform ad hoc analysis both before and after running, should perform bidirectional modeling (the ability to run the same model forward as a simulation or backward as a planning tool), and should outline criteria for what constitutes robustness in a plan.

Over the last two years, we have developed a prototype of a KB mobility model using declarative, causal rules to demonstrate the principles of the technology, including the ability to run the model both forward and backward. We then tested this prototype to examine several scenarios provided by ARPA and USTRANSCOM. These scenarios include one moving almost 10,000 cargoes on four different types of transportation over 140 routes or channels. Our prototype runs this scenario to completion in approximately 10 minutes on a Hewlett-Packard 9000 computer, producing a history file of about 9,500 events. This history file can then be used to answer ad hoc queries in as little as one second.

ADVANTAGES OF CAUSAL, DECLARATIVE MODELS

KB models offer a number of advantages over traditional simulations. KB models are "declarative" in nature. That is, they describe *what* a system does, not just *how* it does it. KB models are also more "formal" than traditional simulation models. They can be analyzed using techniques from formal mathematics and logic. This characteristic allows them to produce analytic capabilities unavailable with conventional simulations or most other kinds of models. For example, KB models can reason about themselves, answering questions such as "Is it ever possible for X to happen?" or "What might conceivably cause Y to occur?" The declarative nature of KB models also makes them easier to understand and, therefore, to modify and validate.

Our KB approach uses rules that specify the causal relationships among events. This approach allows analysis of what *can* cause a given event or what *did* cause a specific event in a simulation run. In contrast, conventional simulation models embody only informal, implicit notions of causality, and they can show only what happened in a simulation run, not what caused it or could have caused it. Our prototype also distinguishes management "decision" rules from physical causality rules. This characteristic allows identification of the types of causes that produce a given result and allows analysis of how management decisions affect an outcome.

Some of the KB rules we use specify how the values of major system variables (for example, the number of cargoes and transport vehicles) depend on various events. The value of a system variable at any particular point in time can be computed from the event history (a list of all the events that occurred during a specific run of the model). The set of rules and the event history can also allow the analyst to ask ad hoc questions that the prototype was not originally designed to answer. In contrast, conventional simulations can answer only questions about system values defined prior to running the simulation, and ad hoc questions can be addressed after a simulation run only by tedious postprocessing of data produced by the run.

The ability to pose ad hoc queries to the prototype provides a major advantage to mobility analysts. With conventional simulations, a model run is typically set up to understand the implications of cer-

tain starting conditions or of specified changes to the model's parameters or assumptions. The insight gained from such runs is limited to the specific cases represented by the inputs, parameters, and assumptions contained in the model setup. That is, conventional simulations cannot easily help analysts address issues beyond those specified in the initial model setup. To consider other issues, another run of the model must be set up and the model executed again. Because setting up model runs, running the model, and interpreting the results typically require considerable effort, it takes analysts a long time to understand the effects of various changes to the system being modeled.

As discussed above, declarative models greatly reduce the need for additional setups and runs of the model. Generating an event history in combination with the causal rules permits the analysts to ask the model questions about what happened and what might have happened. This capability also allows the analyst to address questions that were not originally of interest when a model run was formulated. This capability reduces the time needed for analysis and allows the analyst to obtain a greater understanding of the factors and events that drive system results. Figure 1 compares this aspect of a KB model with a traditional model.

Our KB prototype answers many types of queries, such as, "What are the values of parameters at any point in the simulation run (after some event has occurred or at any time)?" It can also trace all changes to a parameter, showing all events that had effects on the parameter. It can even show which events *can* (ever) affect a parameter in the model, as well as which events *did* actually affect it during a given run. New parameters can be defined after running the simulation, such as the cost per day for using a vehicle of a given type and the cumulative cost at this rate over time. Ad hoc queries can address these new parameters just as if they had been defined before running the simulation. For example, having defined the cost rate over time for a vehicle, we can ask for its cost for a given period and receive the answer without a new simulation run.

In addition to the queries discussed above, our KB prototype can answer other kinds of questions and perform other types of analysis. It can calculate aggregate measures, such as sums of predefined or ad

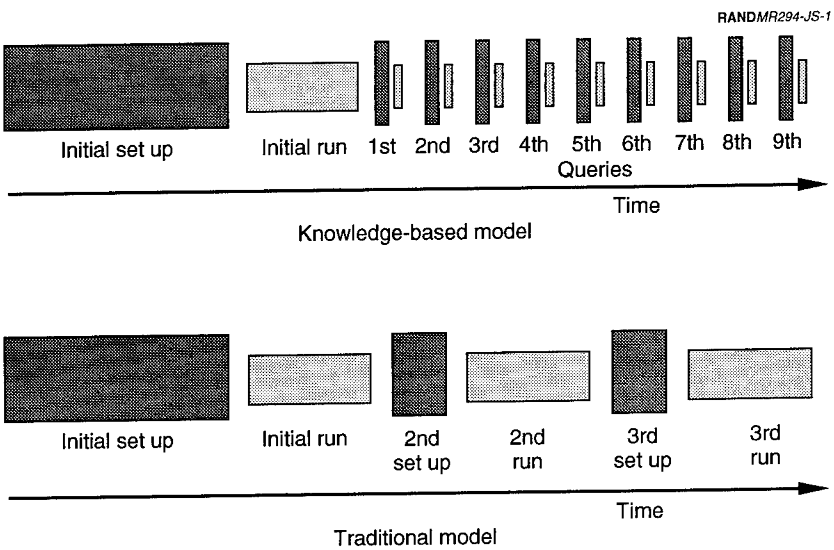

Figure 1—Knowledge-Based Models Facilitate In-Depth Analyses

hoc parameters. It can identify cargoes that remain unshipped at the end of a run. And it can perform simple planning functions, such as finding a sequence of events that can achieve a desired goal.

DIRECT, INTERACTIVE VALIDATION

The formalism of our KB approach also provides a novel capability for direct, interactive validation, in which the user witnesses causal relationships and their effects directly as a model runs, rather than having to infer them from the model's behavior. This capability helps the user understand the behavior of a model without having to understand its implementation. Instead of showing a confusing sequence of actions, our procedures show which events cause which subsequent events. This process produces a direct correspondence between the observed behavior of the model and the causal behavior of the system being modeled. The user need not verify that the model correctly implements the causal behavior of its rules, since this is guaranteed by the formalism itself: If the rules in our prototype express the intended causal relationships, then the formalism

guarantees that its behavior is correct. Instead, the user can directly and interactively validate the model with respect to the real world. Instead of having to ask "Why did the model do that?" the user is able to ask "Is that the actual cause and effect in the real world?" Although there are other approaches in which the readability of a simulation program helps the model-builder ensure that the model is reasonable, our formalism adds to this the ability to witness the underlying validity of the model as a simulation unfolds.

INTEGRATION OF PLANNING WITH SIMULATION

Because KB models consist of rules, they can be interpreted forward or backward. That is, the models can act much like a conventional simulation, by allowing specification of the starting conditions and the "rules" of the system and then simulating outcomes. Or they can work in the other direction, beginning with a specified desired outcome and working backward to determine how it can be achieved (what events must occur or must not occur). This backward solution assists planning functions, helping planners understand what needs to be done to achieve desired conditions or outcomes.[1]

INVESTIGATION OF ROBUSTNESS CRITERIA

A plan is robust if it is fairly insensitive to variations in initial conditions or assumptions. Additional rules in our KB models assist planning by defining "robustness criteria," essentially heuristics that are likely to produce robust plans. For example, one such heuristic might state that a plan will be robust if there are several ways of achieving each step along the way to the desired goal; an alternative heuristic might state that a plan will be robust if its sub-plans remain relatively independent of each other. While there is no guarantee that a plan will be robust if it satisfies such criteria, they provide the model with alternative strategies for attempting to produce robust plans by controlling the planning process. This attribute needs much more development.

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[1]We will discuss further the general concept of solving for transportation resources rather than arrival times in the following chapter in connection with mathematical programming.

STATUS OF THE DEVELOPMENT

Our prototype KB mobility model is a simplified fort-to-foxhole transportation model, which uses notional data for land transportation (i.e., trucks) but fairly realistic data (from USTRANSCOM) for port-of-embarkation (POE) to port-of-debarkation (POD) transport by ships and planes. It takes simplified time-phased force deployment data, derived from scenarios provided by ARPA and USTRANSCOM, extracts what it needs to create its own scenario file, performs cargo aggregation and mode selection (in a manner roughly equivalent to existing transportation simulations), and models cargo movement, employing simple—but generalizable—models of a number of decisionmaking processes, including the assignment of vehicles to channels and of cargoes to vehicles, deciding when to dispatch vehicles based on their loading, etc. The model can be run as a simulation, producing a history of events, such as the loading and unloading of vehicles, departures and arrivals, and all decisions surrounding these physical events. Simulation runs are controlled by the scenario file, so that variations of a given scenario can be run simply by modifying the scenario file.

In addition, many kinds of analysis can be performed on the history generated by a particular simulation run, and other kinds of analysis can be performed on the model itself, independent of any scenario or simulation run. For example, after a simulation run has produced a history, the user can ask causal questions, such as what caused a particular cargo to arrive late or what led to a particular decision to allocate a vehicle of a particular type to a particular channel. The user can also ask unanticipated questions, such as how much it cost to employ a particular vehicle for a particular purpose, even if the cost of employing vehicles was not previously defined in the model: This simply requires writing a few short rules that define how the cost of employing vehicles changes when relevant events occur. Ad hoc queries of this kind can be answered without rerunning the simulation by using the history of a previous run; therefore, such questions can typically be answered on the order of 100 times faster than by rerunning the simulation (i.e., in seconds, rather than tens of minutes, for the largest scenarios we have run). Independent of any scenario or simulation run, the user can ask questions about the model itself. For example, the prototype can show all the events that can cause a particular event of interest to occur or what chains of

events can result from a particular event. The prototype can also generate simple plans for how to arrive at a desired goal event, given a starting event and a criterion for generating robust plans. Since queries like these depend only on the model, and not on a scenario, they can typically be answered in a matter of seconds.

SUMMARY

Our prototype development has demonstrated a number of KB modeling techniques that appear to offer significant advantages over other modeling approaches for transportation analysis. These advantages fall into four categories:

- Making models more understandable and therefore more credible
- Building bidirectional, multipurpose models that can trace causality both forward (to perform simulation) and backward (to perform goal-oriented analysis, such as planning) to provide greater analytic insight
- Building models that apply user-defined criteria for what constitutes robustness in a plan to produce more robust plans
- Building models that can answer unanticipated (ad hoc) questions to facilitate a wider range of analysis.

Many questions remain to be answered and many avenues remain to be explored. The previous pages have indicated places where we see payoffs from this approach; these represent strategies we feel the JS should pursue in developing its next generation of strategic mobility models. In particular, we nominate several research directions as especially worth pursuing in the immediate future.

First, we recommend the continued development of goal-directed modeling techniques exploring the integration of planning with simulation. This development requires further research into a number of issues in bidirectional modeling and reversible simulation. Second, we recommend exploring unresolved issues surrounding the use of robustness criteria in planning. Third, we recommend developing additional techniques for generating object-oriented views of models, for example, to visualize relationships among objects and to

explore the idea of user-defined "macro events" for aggregating the behavior of the model, allowing it to run at varying levels of resolution. Finally, we recommend continuing the development of techniques for providing end-users (i.e., analysts or decisionmakers) with better ways of viewing the structure and behavior of a model and with easier ways of defining and modifying models.

Chapter Three

BROADER TRADE-OFFS USING MATHEMATICAL PROGRAMMING

Mathematical programming (MP) is an established and widely used analysis tool in the operations research and management science fields. MP models develop the optimal solution (either the maximum or minimum) for a specified objective function, subject to a set of system constraints.

However, MP models offer more than just the optimal solution to a problem. Auxiliary measures describe where and when system assets (e.g., ports, ships, or aircraft) are fully used and where some are idle. Sensitivity measures indicate the change in the objective function when additional assets are added to the system. For example, sensitivity measures can show how much the objective function would be reduced if an additional aircraft or ship was added to the transportation fleet or if specified port capacities were increased.

Although MP models have been available for some time, they have had limited practical application to military mobility studies because they require extremely large numbers of calculations to solve complex problems. The number of calculations increases exponentially with each new variable (e.g., each type of cargo or type of aircraft). Although advanced procedures and solution algorithms have somewhat offset this disadvantage, large problems can still require trillions of calculations. However, modern computers with greatly increased capabilities are allowing mobility models to become more and more realistic.

In this study, we used off-the-shelf software running on standard Sun workstations to solve several versions of one of the JS's latest scenar-

ios. As part of the process we learned some important lessons about data aggregation.

THE SCENARIO AND DATA SET

To demonstrate the capabilities of MP models, we used data developed by the JS/J4 for one contingency considered in the Mobility Requirements Study. Table 1 shows some characteristics of the scenario. It considers five types of aircraft and many types of ships. The aircraft include three military cargo designs, the C-5, C-141, and C-17, and two commercial designs, a long-range, wide-body cargo (LRWC) design (the 747) and a long-range, wide-body passenger (LRWP) design (the 767). For our demonstration runs, we use the five aircraft types but group the ships into three broad categories—roll-on-roll-off (RORO), bulk, and container. We use fleet averages to represent the capacities and speeds of these ship types. We specify two PODs, one in Japan and one in Korea.

Table 2 shows the transportation assets and options assumed to be available. AMC controls 100 C-5s and 150 C-141s, both of which we designate as out of production. We also assume it has access to some 90 commercial aircraft under Civil Reserve Air Fleet (CRAF) and other long-term arrangements. Government costs for all of these aircraft will be incurred whether the contingency under this scenario occurs or not, so those costs are considered sunk and do not affect the analysis. AMC can also purchase any number of C-17s. These are considered incremental to the scenario and will cost about $500 million each over their assumed 30-year life. More commercial

Table 1

Data Set Characteristics

Item	Counts
Cargoes	5,761
Days	181
Aircraft types	5
Ship types	Many
Origins	52
Destinations	2

Table 2

Transport Vehicles

Vehicle	Baseline Availability[a]	Cost of Augmentation[b]
Aircraft		
C-5	100	na[c]
C-17	0	500
C-141	150	na[c]
LRWC	15	30
LRWP	75	15
Ships		
Bulk	60	400
Container	40	400
RORO	50	425

[a]Number of vehicles assumed under DoD ownership or control, with costs incurred whether contingency eventuates or not.

[b]Thirty-year life-cycle cost, in millions of 1992 dollars, of each additional vehicle. For more detail see Hura, Matsumura, and Robinson, 1993.

[c]These aircraft are assumed to be out of production.

aircraft can also be recruited. We assume their 30-year contingency contracts would cost $30 million and $15 million, respectively, for cargo and passenger aircraft. Finally, we assume MSC controls some 150 ships and can purchase more of each type as necessary.

Most of our model runs identify least-cost means for adding vehicles to the current inventory so that it will have sufficient capability to handle the contingency traffic if the contingency should occur any time within the 30-year planning horizon.

AGGREGATING DATA TO REDUCE COMPUTATION REQUIREMENTS

Because of problems presented with solving large MP problems, we devoted a substantial portion of our early efforts to understanding how we could collapse the detail in our formulation without adversely affecting the final solution.

The size of the problem depends on the range of potential values for the variables in our model: the number of different types of transportation assets, the number of time periods in the scenario, the number of channels (POE-POD pairs), the number of cargoes to be shipped, and the number of different types of cargoes (bulk, over, out, passengers). We examined a number of ways to aggregate the problem so that we could attain solutions in reasonable amounts of time, including the following:

- Combining cargoes with similar characteristics into "packages" of movement requirements
- Aggregating the number of channels by considering port complexes (POEs or PODs in a geographic region) versus individual ports
- Reducing the number of time periods in the model by taking large time steps in our solution procedure or by concentrating on only the peak demand period
- Reducing the number of transportation asset types we considered in the model.

For each of the above methods, we ran a disaggregated model to produce a solution and then ran an aggregated model to compare results. This method identified the types of aggregation that had little or no effect on the final solution and the types that made a significant difference.[1]

As a general rule, any modification (aggregation) of the problem that does not change a binding constraint (one where no excess capacity exists) will not affect the final solution. We found a number of aggregation techniques for which this principle held for the majority of scenarios considered.

Based on those experiences, we have aggregated the almost 5,800 cargoes of the scenario to slightly fewer than 500 (see Table 3). Most of the decrease is due to combining cargoes with the same available-to-load dates (ALDs), required delivery dates (RDDs), POEs, and

[1]These studies are detailed in Mattock et al., unpublished RAND research.

Table 3

Data Aggregation

	Counts for:	
	Full Scenario	Demo Runs
Movement requirements	5,761	490
Days	181	20
Types of aircraft	5	5
Types of ships	Many	3
Origins	52	3
Destinations	2	2

PODs into a "package" of cargoes. That is, all cargoes of a particular type that arrive at a given POE at the same time and are required to be delivered to the same POD by the same time are merged together into one movement requirement.

We also discovered we needed to examine only the peak period of the scenario because the transportation assets required during the most stressful portion of the scenario will be adequate to deliver cargoes during less stressful periods. For our demonstration runs, the peak period runs from day 10 to day 30.

Finally, we aggregated the original 52 continental United States POEs into three "port aggregates," namely the East Coast, West Coast, and Gulf Coast. This is a standard procedure used by most current models. There are two PODs (Japan and Korea) in both the original scenario and in our demonstration runs.

Aggregations are not uncommon in mobility simulations, although some we have used are less common than others. Most mobility models, including "detailed" models like MIDAS and RAPIDSIM, aggregate cargoes and ports. The simulation models, however, especially MIDAS, typically do consider many different types of ships. Concentration on the peak period is less common. In all, the simple procedures we employed reduced the size of the problem and its computational requirements substantially. Most simulations ran in about 10 minutes on our workstations.

DEMONSTRATION OF CAPABILITIES

Given the scenario characteristics and assumptions about transportation assets, the next few pages briefly illustrate MP formulations we believe will substantially increase the capabilities and usefulness of JS studies. These capabilities exist now and can be used in ongoing studies.

Minimizing Transport Costs

Our basic MP formulation minimizes the life-cycle cost of acquiring additional transportation assets (starting with an initial fleet of ships and aircraft) subject to the constraints of delivering all cargoes by their required delivery dates and not exceeding the capacities of ports.

Figure 2 shows the result of the MP run to minimize the cost of transportation assets to deliver all of the cargoes on time. This is the basic resource-requirements question that mobility analysts have for decades used MP models to investigate. The y-axis displays the

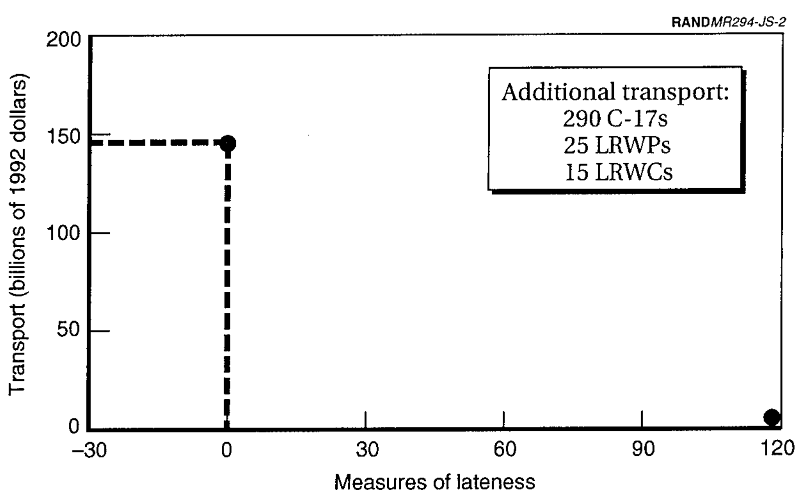

Figure 2—Mathematical Programming Solves for Optimal Set of Transport Assets

30-year life-cycle cost of the additional transportation assets. The x-axis shows a measure of lateness; here we want no lateness, that is, all cargoes delivered by their RDDs. The result shows that, in addition to the available C-5s, C-141s, and ships, we need 290 C-17s, 25 (of the 75) LRWPs, and all 15 of the LRWCs.[2] The 30-year life-cycle cost of these additional assets is approximately 150 billion dollars.

In addition to providing the least-cost set of transportation assets to close the force, the model also shows when specific cargoes are loaded at the POEs, what type of asset they travel on, and when they arrive. The model provides details on when specific asset types are required (e.g., the CRAF aircraft) and where bottlenecks or excess capacities exist in the system.

Trade-Off Between Delays and Transport Costs

For intense scenarios, those that involve substantial amounts of cargo or compressed delivery periods, available budgets may not be sufficient to obtain the needed additional transportation assets. Or interest may focus on how best to use existing assets. When the optimal solution cannot be obtained because of budget constraints, the model can be reformulated to produce the "best" that can be accomplished with whatever assets are available or with some specified additional budget.

Figure 3 shows the results of constraining the transportation assets to what is available (no additional assets can be procured) and minimizing lateness. Here, the objective function minimizes ton-days late, with each cargo and each day-late valued equally. The model suggests (point "B" in Figure 3) that available transportation assets can deliver the force with approximately 120,000 ton-days of lateness. The model also indicates which cargoes are late and when they do arrive. Point A shows the cost of zero lateness from Figure 2.

We can evaluate lateness in several different ways. In the run shown, we viewed each cargo and each day-late as equal. That is, they all

[2]This scenario contains many time-sensitive cargoes and requires the acquisition of many C-17s. These aircraft then can be used, at no additional cost, to deliver most, or all, of the non-time-sensitive cargoes that would otherwise travel by sea.

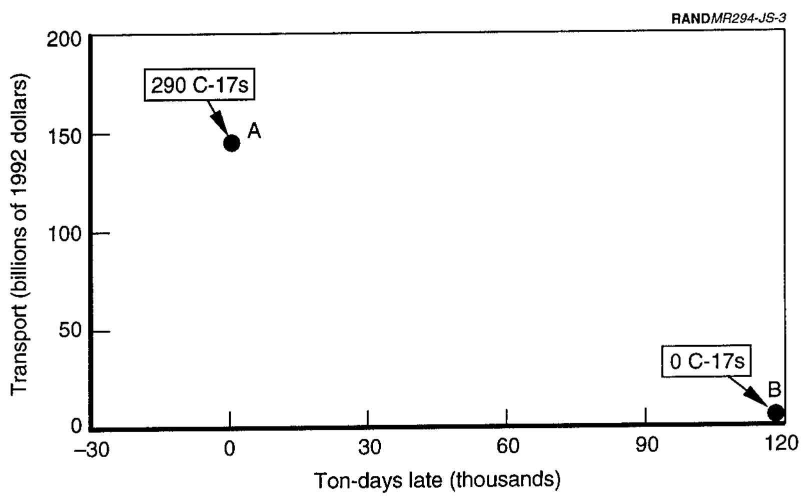

Figure 3—Determination of "Optimal Lateness" for Limited Budget

had the same "penalty" cost for being late. We could have assigned different costs of lateness to different cargoes; for example, we might prefer to have combat units delivered on time at the expense of support units or resupply. Then, we would put a much higher "cost" on combat units' ton-days late and a lower cost for support units or resupply. Also, we could evaluate days late differently. For example, the second day a cargo is late might "cost" more than the first day late. The model has the flexibility to address these various measures of lateness and different lateness "costs" for different cargoes. Using the MP prototype in this manner measures optimal capability of the existing transportation fleet.

To extend this example further, Figure 4 shows the results of two intermediate runs. In one case we have specified an additional budget of 50 billion dollars and asked the model to minimize lateness. Ninety-nine C-17s would need to be procured (in addition to the LRWCs and LRWPs shown before) and the ton-days late would be reduced to approximately 30,000. The second run set an additional budget of 100 billion dollars. The model suggested that 199 C-17s should be bought and the cargo would be a total of approximately 5,000 ton-days late.

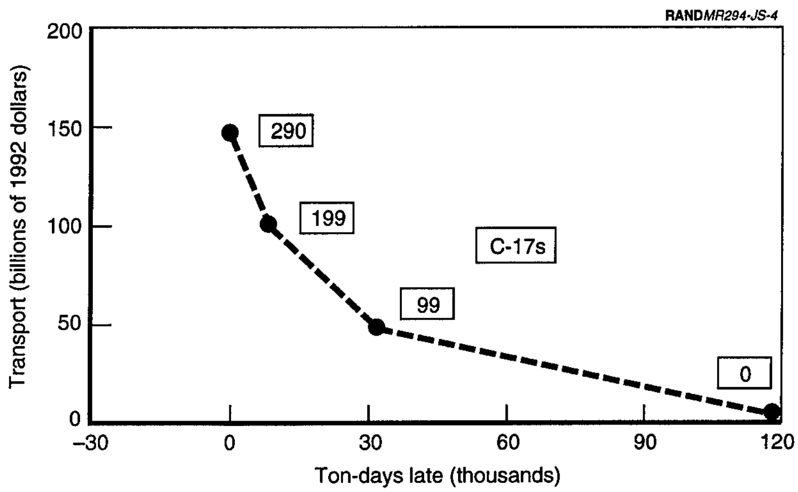

Figure 4—Determination of Trade-Offs Between Cost and Effectiveness

These parametric analyses provide insight into the trade-offs between additional transportation assets and lateness. Note that the function is convex; that is, the benefit of adding additional C-17s diminishes. The first increment of 50 billion dollars reduces ton-days late significantly (by 90,000); the second increment of 50 billion dollars has a much smaller effect (further reduction of almost 25,000 ton-days late); the third increment of 50 billion dollars has only a slight effect (reducing lateness from 5,000 to 0). Given this information, decisionmakers can determine if they are willing to have some cargoes arrive slightly later than planned, reducing transportation costs.

Trade-Off Between Readiness and Transport Costs

Allowing cargoes to arrive later than planned is one solution when transportation assets are limited and budgets are constrained. But there are others. Each cargo can be viewed as having a time window, one edge set at its ALD and the other at its RDD. An alternative to minimizing lateness involves extending the other edge of the time window. That is, if cargoes could arrive at their POEs earlier than

their ALD, it may be possible to deliver all cargoes by their RDD with available assets or with a smaller budget increment than when both edges of the time window remain fixed.

Figure 5 shows the results of several model runs where the RDDs are fixed, and we allow the units to arrive earlier than their planned ALDs. We minimize a measure of "earliness" for existing assets, using an increment of 50 billion dollars to buy additional transportation assets. The top left point is the solution to our "basic" transportation question—the budget required to deliver all cargoes on time with their ALDs fixed. The point on the lower right is the minimum number of ton-days early (at the POEs) that can be attained with current transportation assets. It suggests that if approximately 90,000 ton-days of cargo could arrive at their POEs earlier, current assets could deliver all cargoes by their due dates. The intermediate point shows the number of ton-days early assuming we have 50 billion dollars to procure additional transportation assets.

As with our example of relaxing RDDs, we could formulate this objective function in a number of different ways, and we could "cost"

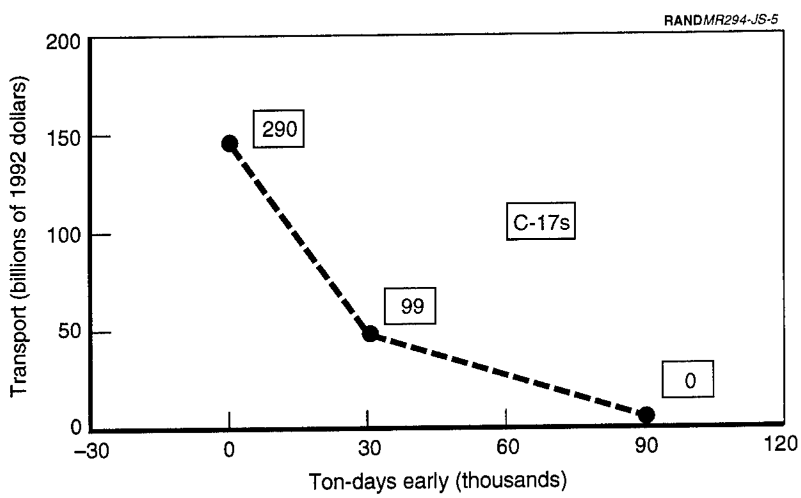

Figure 5—Analyzing Trade-Offs Between Transport Requirements and Cargo Available-to-Load Dates

earliness in different ways (here we value each day early and each cargo the same). The model runs show which cargoes must be early and when they must be at their POEs.

With this formulation, decisionmakers can examine the trade-offs between unit readiness (in terms of unit ability to depart) and transportation costs. It may cost less to have certain units available a few days early than to procure the transportation assets necessary to deliver them on time, leaving on their planned ALDs. Such analyses may also help in selecting which units should be designated to fill a requirement. For example, if an armor division is needed in the theater, the analysis of the ALDs may suggest one armor unit may be preferred over another because it has an ALD that will reduce transportation costs.

Trade-Off Between Prepositioning and Transport Costs

Another way to reduce transportation requirements is to preposition some of the cargoes. Here we can formulate the MP model to minimize the number of tons prepositioned subject to fixed ALDs, RDDs, and currently available transportation assets. Figure 6 suggests that approximately 30,000 tons of cargo must be prepositioned to close the force when desired, using only existing transportation assets. The model also specifies which cargoes must be prepositioned.

In this example, we have again "costed" all cargoes equally. Alternatively, we could define different prepositioning costs for different cargoes and minimize total prepositioning costs. We could also define the objective function as the sum of transportation costs plus prepositioning costs and find the minimum. In that case, we would expect some cargoes to be prepositioned and some additional transportation assets to be procured.

Analyzing Alternative Scenarios

As a final example, we formulate the MP model to address two scenarios at the same time, finding the different sets of transportation assets that will satisfy the scenarios when they occur in sequence or simultaneously.

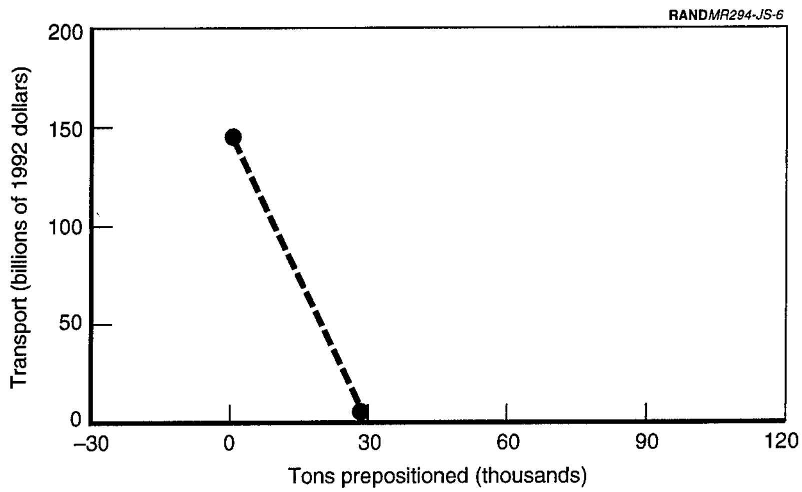

Figure 6—The Benefits of Prepositioning

The new political order in the world has changed the focus of mobility analyses. Before the upheaval in Eastern Europe and the breakup of the Soviet Union, mobility analysis concentrated on a NATO versus Warsaw Pact scenario. The transportation requirements associated with that scenario far outweighed the assets needed for any other eventuality, so analyzing the one scenario sufficed. Now, however, the mobility community must address numerous scenarios in diverse regions of the world. The Mobility Requirements Study addressed several major and minor scenarios.

We demonstrate how the MP prototype can determine the optimal set of transportation assets when looking across several scenarios. Consider an example. Scenario A places heavy demands on airlift but virtually no requirements on sealift. This is the scenario examined above. Scenario B makes heavier demands on sealift. Table 4 shows some characteristics of the two scenarios, both of which were developed by the Joint Staff for the Mobility Requirements Study. We chose these scenarios, and a lengthy peak period for each, in order to stress our formulation and our MP solver.

Table 5 shows the output for this last set of demonstration runs. It shows the transportation vehicles required to deliver all cargoes on

Table 4

Data Sets

Item	Counts			
	Scenario A		Scenario B	
	Full Scenario	Demo Runs	Full Scenario	Demo Runs
Movement requirements	5,761	1,258	11,942	8,595
Days	181	75	228	75
Types of aircraft	5	5	5	5
Types of ships	Many	3	Many	3
Origins	52	3	66	4
Destinations	2	4	16	2

Table 5

Transport Required for Two Scenarios (all cargoes delivered on time)

Vehicle Type	Baseline Availability	Vehicles Used, by Scenario			
		A	B	A *or* B	A *and* B[a]
Aircraft					
C-5	100	100	100	100	100
C-17	0	290	247	290	290
C-141	150	150	150	150	150
LRWC	15	15	15	15	15
LRWP	75	24	42	42	42
Ships					
Bulk	60	0	6	0	0
Container	40	0	40	40	40
RORO	50	0	50	50	50
Incremental costs (billions of 1992 dollars)		$146	$125	$146	$146

[a]In the A and B scenario, the peak period for scenario B is programmed to begin 30 days after the peak period for scenario A begins.

time for four scenarios: A alone, B alone, A or B, and A and B. For the A and B case, the peak period for scenario B was programmed to begin 30 days after the beginning of the peak period for scenario A.

As noted previously, scenario A contains many time-sensitive cargoes requiring the acquisition of a large number of C-17s. These air-

craft can then be used, at no additional cost, to deliver most or all of the cargoes that would normally travel by ship.[3] Scenario B, on the other hand, contains significantly more cargoes, but most scenario-B cargoes display less time sensitivity and consequently can travel by ship. Note that these ships, although they are not used in the other cases, do not increase the incremental cost because they are already owned by, or are under lease to, the military. The reduction in the buy of C-17s, however, does significantly reduce the required expenditures.

When we enter both scenarios in the model and solve for the vehicle set that most efficiently serves scenario A or scenario B, that set turns out to be, not surprisingly, almost the maximum of the two individual sets. All 290 C-17s are still required to deliver all of the scenario-A cargoes on time, and almost all of the ships used to service scenario B alone are still needed despite the additional 43 aircraft.

Finally, we address the near-simultaneous occurance of A and B by treating the two scenarios as one and computing a least-cost set of assets to handle the total movement requirements. For these particular scenarios, however, the set of vehicles required to deliver all goods on time in the A and B, near-simultaneous case turns out to be the same as that of the A or B case. This is because the peak demands for aircraft do not overlap. In fact, the peak airlift requirement for scenario A is sufficiently large that those planes can carry most of the later non-time-sensitive cargoes for both scenarios.

[3]A nominal cost for using "owned" ships and aircraft for the first time induces the model to use an available already-used vehicle before using an available but previously unused vehicle.

Chapter Four

CONCLUSIONS

In Task 4 of our research for the JS/J4, we developed knowledge-based prototypes and demonstrated mathematical-programming formulations designed specifically for the JS.

DEVELOPMENT OF KNOWLEDGE-BASED PROCEDURES

The KB prototypes continue to promise significant advantages over other modeling approaches for transportation analysis. To date, we have

- implemented KB modeling techniques in a rule-based prototype strategic mobility model
- demonstrated tracing and analyzing causality both forward and backward, performing simulation and goal-oriented analysis using the same model
- demonstrated ways of applying user-defined criteria for robustness, to drive goal-oriented analyses and to produce more robust plans
- demonstrated the ability to answer unanticipated (ad hoc) questions after running a simulation, by simple queries to the saved history of events
- demonstrated that our KB approach can "scale up" to handle scenarios of significant size (e.g., simulating the movement of 10,000 cargo items by four types of transportation over 140 routes in about 10 minutes of computation time on a Hewlett-Packard 9000 workstation).

This developmental research continues. Fiscal year 1994 work for the JS/J4 coordinates with the General Research Corporation on the integration of KB procedures into a revised version of MIDAS.

DEMONSTRATION OF MATHEMATICAL-PROGRAMMING CAPABILITIES

During the last years of Task 4, we focused the majority of our efforts on the JS's most pressing strategic mobility need, the need for models and analyses of trade-offs balancing troops, transport, and cost. We formulated a number of MP models that demonstrated the following capabilities:

- Directly determining the least-cost set of transportation assets to close all deploying forces and support by their RDDs.
- Determining the minimum amount of lateness, measured in various ways, given an existing set of transportation assets and a limited budget to buy and operate more. The outputs identify which cargoes are late and how late they are.
- Determining the minimum amount of earlier availabilities needed to allow an existing set of transportation assets and a limited budget to deliver all cargoes on time. The outputs show which cargoes require earlier ALDs and how much earlier than planned they must be.
- Determining the minimum amount of prepositioning needed to allow an existing set of transportation assets and a limited budget to deliver all cargoes on time. The models show which cargoes require prepositioning.
- Determining, by combining the above procedures, the most effective way of allocating limited funds among readiness, transport, lateness, and prepositioning.
- Determining the minimum cost specification of transport needed to respond to multiple scenarios sequentially or simultaneously.

These techniques greatly expand the JS's strategic mobility analysis capabilities and allow detailed investigation of issues that previously had to be ignored because of the shortcomings of its analysis tools.

Advances in computer hardware and software and in the algorithms used to solve large MP problems now allow these techniques to be viable. Some detail must be aggregated in reducing the size of large scenarios, but analyses suggest such aggregations can be accomplished without adversely affecting the identification and specification of the solution. These MP capabilities exist now and can be used in current strategic-mobility studies.

FURTHER RECOMMENDATIONS

For the future, we recommend research into the integration of the KB and the MP procedures. Each approach provides certain advantages. And each currently has shortcomings. The optimization approach directly determines the least-cost set of assets but does so with some loss of detail and by assuming that the world operates in an optimal fashion. KB simulations capture details and provide more realistic representations of real-world activities but do not currently balance trade-offs among transport assets, procedures, and costs. Integration of the methods should allow analysts the advantages of each in addressing the full range of strategic-mobility problems.

Nearer-term advantage may come from coordinated use of the two types of models. After the KB procedures mature and are integrated into simulation models of transport operations, they can provide important checks on the validity of solutions obtained through the MP models. That is, an MP model can be used to identify the best mix of forces, transport, and cost for an aggregated problem. That solution can then be input to a KB model to test transport operations in a more detailed representation of how the real world operates. Shortfalls indicated by the KB simulation can then be used to calibrate the parameters and factors of the MP model.

BIBLIOGRAPHY

Hura, Myron, John Matsumura, and Richard Robinson, *An Assessment of Alternative Transports for Future Mobility Planning*, Santa Monica, Calif.: RAND, R-4245-ACQ, 1993.

Joint Data System Support Center, *Rapid Inter-theater Deployment Simulation Model (RAPIDSIM) User's Manual (DRAFT)*, September 1985.

Keyfauver, Carrolly, *Model for Intertheater Development by Air and Sea (MIDAS), Version 2.9.2, User's Manual*, General Research Corporation, 1419-03-87-CR, February 1987.

Mattock, Michael G., John F. Schank, Jeff Rothenberg, and James P. Stucker, *New Capabilities for Strategic Mobility Analysis Using Mathematical Programming*, unpublished RAND research.

Moore, S. Craig, James P. Stucker, and John F. Schank, *Wartime Roles and Capabilities for the Unified Logistic Staffs*, Santa Monica, Calif.: RAND, R-3716-JCS, February 1989.

Rothenberg, Jeff, James P. Stucker, Michael G. Mattock, and John F. Schank, *Knowledge-Based Modeling for Strategic Mobility Analysis*, unpublished RAND research.

Schank, John, Michael Mattock, Gerald Sumner, Irwin Greenberg, Jeff Rothenberg, and James P. Stucker, *A Review of Strategic Mobility Models and Analysis*, Santa Monica, Calif.: RAND, R-3926-JS, 1991.

Schank, John F., James P. Stucker, Gerald Sumner, and Michael G. Mattock, *Enhancing Joint Capabilities in Theater Ammunition Management,* Santa Monica, Calif.: RAND, R-3789-JS, 1991.